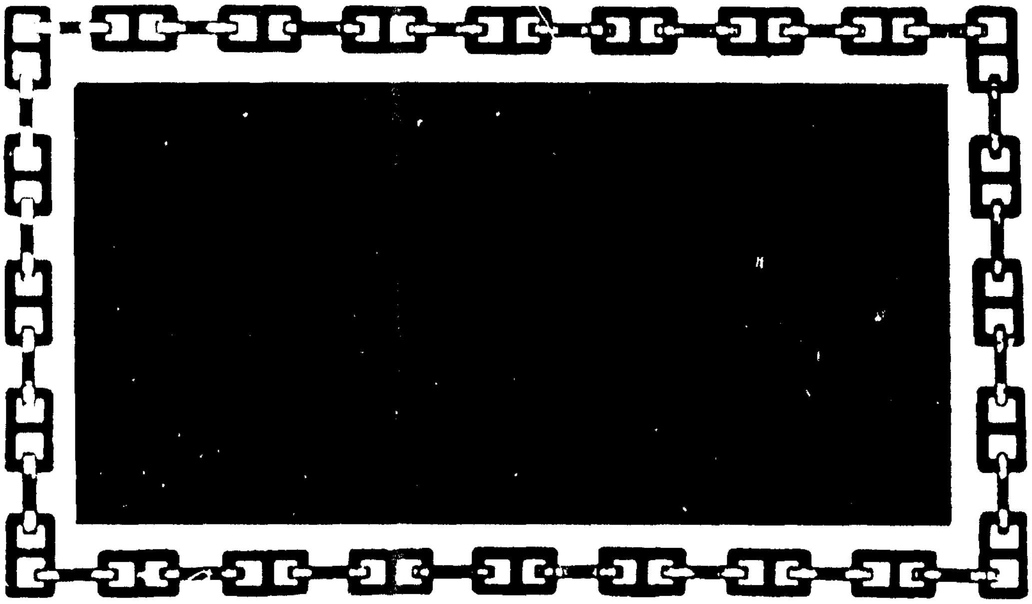
DEPARTMENT OF THE NAVY
BUREAU OF SHIPS

DEPARTMENT OF THE NAVY
EXPERIMENTAL DIVING UNIT



U. S. NAVY EXPERIMENTAL DIVING UNIT

EXPERIMENTAL DIVING UNIT
UNITED STATES NAVY

U.S. NAVY EXPERIMENTAL DIVING UNIT
WASHINGTON NAVY YARD
WASHINGTON, D.C.

RESEARCH REPORT 4-65

CARBON DIOXIDE ABSORPTION SYSTEMS FOR SCUBA
2. THEORY AND APPLICATIONS OF A NOVEL, NON-CYLINDRICAL LOW-RESISTANCE, CO_2 ABSORPTION CANISTER FOR SCUBA

PROJECT SF-011-06-05, TASK 11511, SUBTASK 4
(REPORT NO. 2)

BY
M.W. GOODMAN, LCDR (MC), USN
AND
T.W. JAMES, HM1(DV), USN

15 JUNE 1965

SUBMITTED:

M.W. Goodman

M.W. GOODMAN, LCDR (MC), USN
ASS'T SUBMEDRESEARCH

APPROVED:

R.D. Workman

R.D. WORKMAN, CAPT (MC), USN
SUBMEDRESEARCH

APPROVED:

C.H. Hedgepeth

C.H. HEDGEPETH, CDR, USN
OFFICER IN CHARGE

ABSTRACT

Results of underwater swimming experiences, breathing-machine experiments, and recompression-chamber testing to eleven atmospheres absolute pressure (330 feet sea water) with new SCUBA carbon dioxide absorption canisters are reported. Granular Baralyme was employed as the chemical absorbing agent. Certain comparisons, both of design and functional history, with conventional cylindrical canister systems are emphasized and analyzed, and theory of the low-resistance device is discussed.

As a three-dimensional geometric solid, the essential canister shape is that of a frustum of a rectangular pyramid. In the two-dimensional aspect of greatest surface the canister perimeter presents as a truncated isosceles trapezoid. Inlet and exhaust hose fittings are situated near the extremes of the larger rectangular base of the canister. The acronyms FLATCAN and Flatcanister denote Flat, Low resistance, carbon dioxide Absorption, Trapezoidal Canisters.

Mean ΔP and resistance results for nine cylindrical canisters (16 mechanical respirator experiments) are about 90% and 150% higher, respectively, than the comparable mean data for seven FLATCAN prototypes (15 respirator experiments). A Reynolds number comparison, measured with a Fisher t test, was significant at the 0.01 confidence level.

Size and dimensional parameters have been empirically related to duration of satisfactory carbon-dioxide elimination from SCUBA systems.

SUMMARY

PROBLEM

1. Design, laboratory testing and underwater-swimming evaluation of prototype canisters with adequate carbon-dioxide elimination functioning, minimal impedance to expired gasflow, and practical handling characteristics, for use with self-contained diving apparatus (closed circuit and semi-closed circuit devices).

FINDINGS

1. With identical testing conditions and influences, granular Baralyme-charged Flatcanisters were observed to have only two-tenths to one-half the pressure drop, at peak flow, of comparable-capacity cylindrical canisters.

2. Flatcanisters do not exhibit as large a magnitude of resistance increase, with use time, as that which is characteristic of cylindrical canisters.

3. Flatcanisters are less efficient air-stream cleansers than comparable-capacity cylindrical canisters. Although usually not required, this can be compensated by adjusting absorbent capacity according to empirically-developed duration-dimensions-capacity tables.

RECOMMENDATIONS

1. This alternative to conventional, cylindrical SCUBA canisters be considered for use with proposed equipments which are to be employed in closed-circuit oxygen swimming and with both closed and semi-closed circuit mixed-gas diving whenever the consequences of higher-range flow resistances are anticipated.

2. Adaptation for rescue breathing apparatus and metabolism-measuring equipment be considered.

3. Appropriate feasibility or evaluation studies of non-corrugated flexible hose be initiated.

ADMINISTRATIVE INFORMATION

Project designation: BUSHIPS Project SF-011-06-05, TASK 11511 SUBTASK 4, "Carbon Dioxide Absorption Systems for SCUBA".

Project chronology: This manuscript constitutes project report number two, and was submitted on 15 June 1965. The project outline was submitted on 3 August 1964 and project report number one was dated as of 15 January 1965.

Personnel: T. W. JAMES, HM1(DV), USN fabricated the prototype canisters, designed the tension-bar cover assembly, conducted the mechanical respirator runs and served as chief project engineer. C. W. DUFF, HMC(DV), USN and P. LAFERRIERE, HM1(DV), USN conducted the underwater swimming tests with characteristic competance.

Manpower expenditure estimates are as follows:

DESCRIPTION		
Underwater swimming evaluation series:	subjects, 30	
	tenders, 150	180
Recompression chamber evaluation series:	subjects, 8	
	tenders, 20	28
Mechanical respirator evaluation series		100
Fabrication and alteration of canisters		90
Canister design, data analysis and calculations		200
Preparation of report		75
Drafting and typing services		35
	TOTAL	708

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background. Fundamental prerequisites to the study, design and assembly of optimum diving systems composed of (a) equipment, i.e., hardware, and (b) man, are complete knowledge of the effects of the environment upon the equipment, the effects of the environment upon human physiology, and the effects of the equipment itself upon the man. The orientation of this project work, referenced to the last-noted prerequisite, has been the diver himself, by assuming him to be the essential element in the diving system, and by stipulating that maintenance of his well-being governs the entire system. Flow resistance properties of the cylindrical SCUBA canisters are, generally, incompatible with this manner of approach.

1.2 Objective and Scope. Sections of project report number one (4) were devoted to concepts, intentions and procedures which then promised to be applicable to each phase of this study. One of the project tasks or areas has been designated, "Studies of novel canister designs, with granular Baralyme". Specifically, the current objective has been development and testing of a radical canister principle (patent pending) and prototoiypes, as alternatives to conventional, cylindrical canisters. The area of concern is limited to gasflow and resistance effects, and is distinct from an inquiry into cylindrical canister carbon dioxide elimination efficiency, which has usually proven to be adequate.

2. METHODS

2.1 General. Essentials of mathematical and experimental procedures, as well as estimations of accuracy and validity for laboratory tests with the cam-actuated piston respirator and subsurface, underwater swimming runs, have heretofore been documented (2)(4)(6). Methodology for gas analyzer and pressure sensor calibration and utilization techniques, except those to be introduced in paragraphs 2.2.1 and 4.6.5, was extended particular attention.

2.2 Dry Chamber Runs

2.2.1 Data Acquisition in Subjective Tests. Canisters were prepared and packed in a routine manner. Pressure sensing was accomplished with Statham PR-23 temperature-compensated, 5 Cm Hg. differential pressure transducers, and Sanborn model 350-1100B carrier preamplifiers mounted in the cabinet of a Sanborn 964 four-channel hot-stylus oscillographic recorder. Pressure-sensing taps were rigidly flush-mounted, with reference to the internal surface of the monitored conduit, at least four conduit-diameters distant from canister inlet and outlet fittings. Transducer tap lumens permitted passage of a number 53 drill, and opened tangentially to the reference surfaces a SCUBA mouthpiece of the type used with the USN standard closed-circuit oxygen apparatus, the inlet or exhaust hose fitting of a test canister, or the inlet and exhaust fittings of breathing bags.

2.2.2 Standard Setup. A two-foot segment of standard, one-inch I.D. corrugated SCUBA hose was used to connect the exhalation side of a mouthpiece-breathing valve assembly to the canister. Ambient chamber air was inhaled through a Wright respirometer and an eighteen-inch length of SCUBA hose.

2.2.3 Tidal Volume Measurement. The Wright respirometer was carefully calibrated with both steady square wave, and sinusoidal deliveries of measured volumes of 100% helium and compressed air, at one, two and four atmospheres absolute ambient pressure, and readings were found to vary according to the mass velocity of the calibration gas. McDowell (10) has reported that, at two atmospheres (air) pressure, the Wright respirometer overread by eighteen percent. This finding agrees, precisely, with our independent observations.

2.2.4 Sequence. These tests were performed by the same subject, breathing through the open-circuit test setup. Sequences of normal, resting and rapid, deep respirations began with an inhalation marked by remote signal on the chart-paper time base. As reported in Table 8, evaluations by the breathing machine technique were also performed at simulated depths in the recompression chamber. For each of these brief intervals, consisting of about eight to twelve stroke volumes, the test gas was ambient air without admixed carbon dioxide or humidification. Routines were not commenced until ambient chamber atmospheric air temperature had stabilized at the test pressure level. Depth measurement was determined with Wallace and Tiernan type FA-234 Bourdon tube gauges, with dials custom calibrated at one foot intervals between zero and 1100 feet sea water (1 foot S.W. = 0.44357 PSI).

3. RESULTS

3.1 Tabular summaries. Parameters of canister size, absorbent loading and dimensions comprise the first two of the following group of tables. Test conditions of airflow, carbon dioxide delivery, etc., are reported in Table 3, and results of the mechanical breathing machine tests follow in tables four and five. Swimming run and dry chamber run results are tabulated, respectively, in tables 7 and 8.

3.2 Illustrations. The terminology and dimensional notation of figures 2A and 2B is used both in the tables and in the discussion text. Figure 3 illustrates the total elapsed time, actual O.8K. swimming time and the resting intervals for a quartet of subsurface exposures with Flatcanister closed-circuit oxygen rigs. Data points are relatively sparse because each time that gas is withdrawn from the rig and the diver, the system is converted from closed to semi-closed in nature, with consequent effects upon canister duration proportional to the amounts of carbon dioxide thus eliminated and the volumes of supply gas makeup via the bypass mechanism. Pressure-drop observations are related in Figure 5.

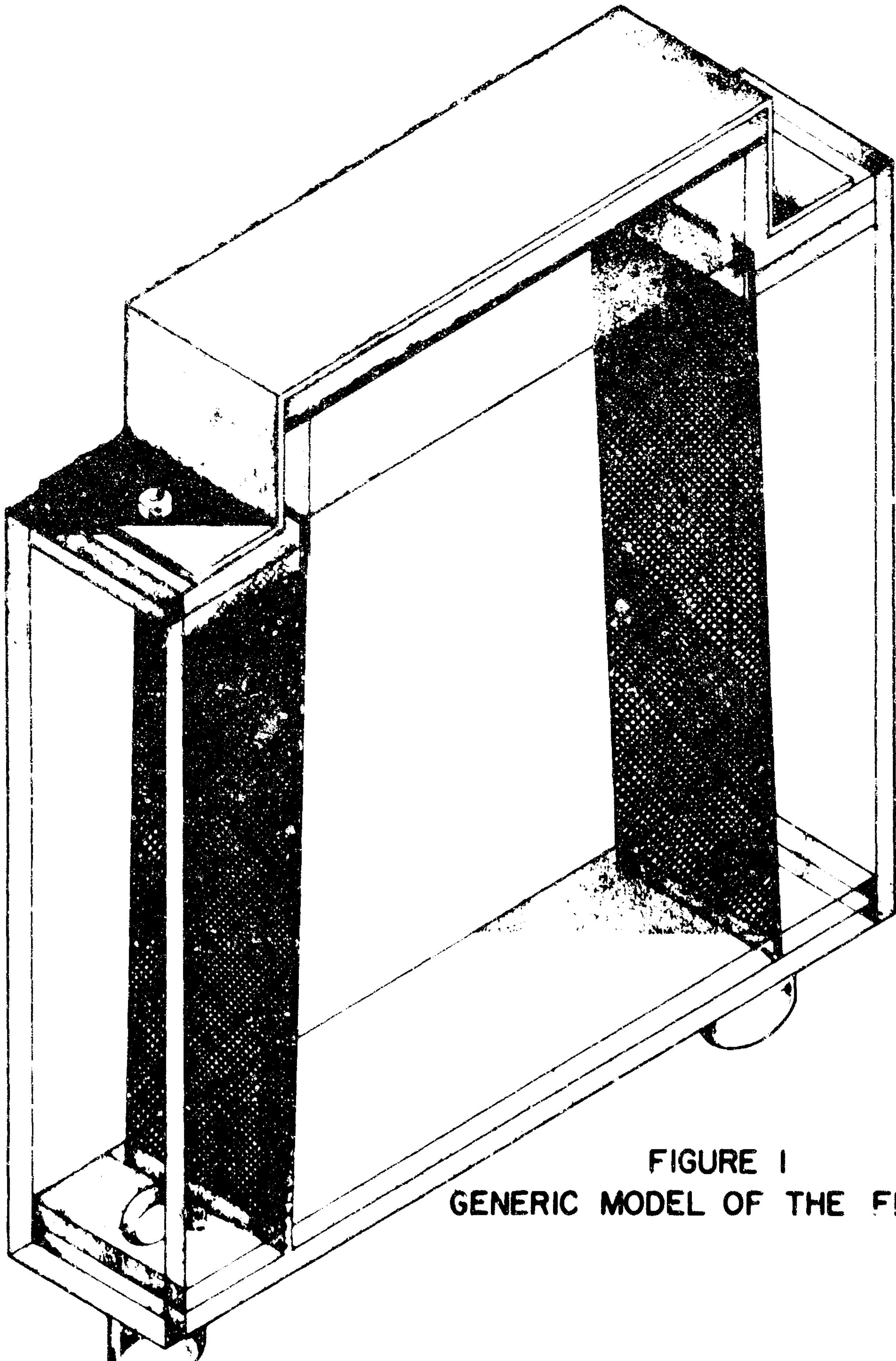


FIGURE 1
GENERIC MODEL OF THE FLATCAN

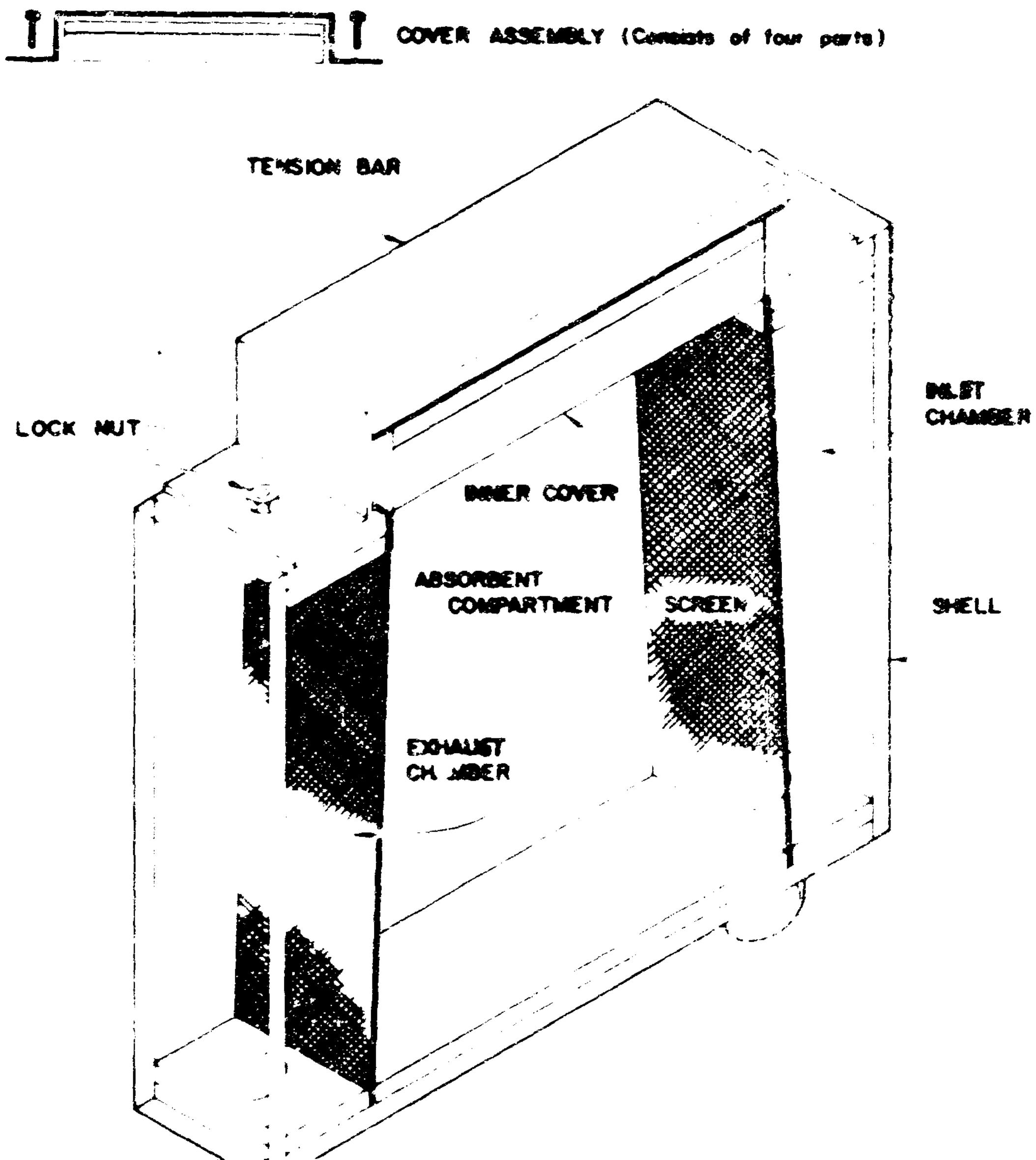


FIGURE 2A
COVER ASSEMBLY, COMPONENTS AND CHAMBERS

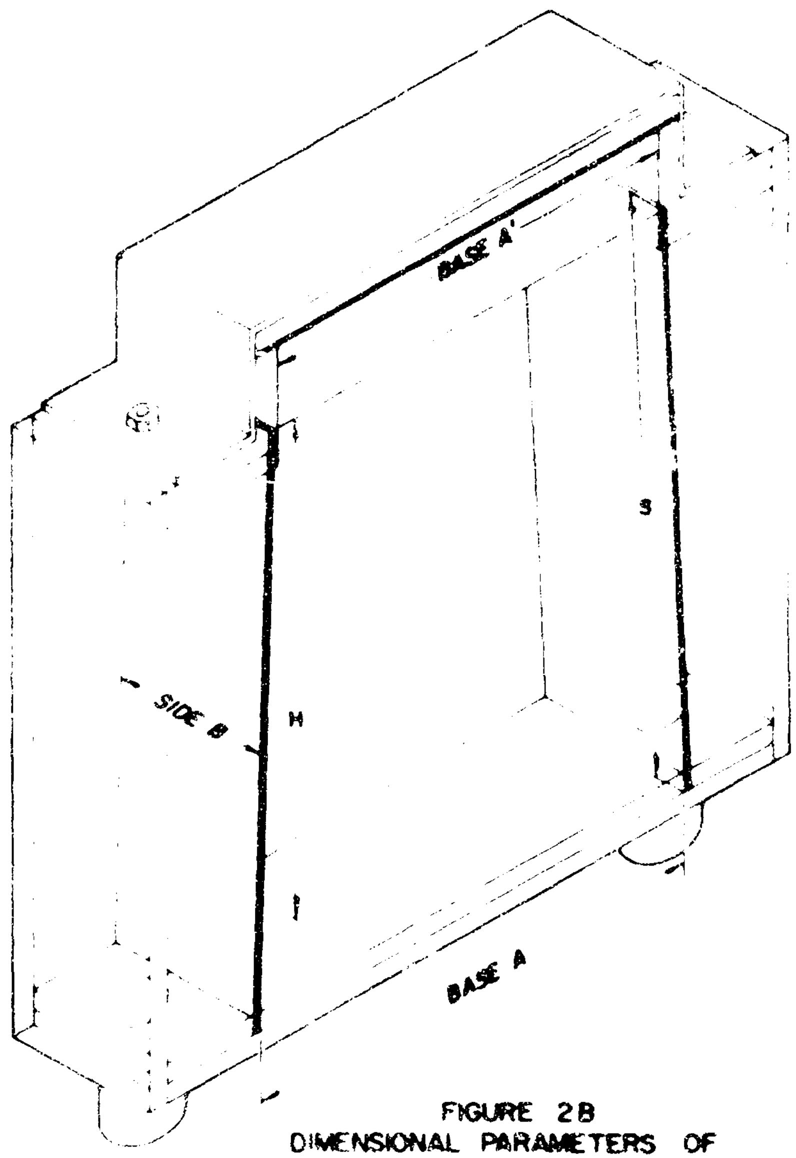


FIGURE 2B
DIMENSIONAL PARAMETERS OF
LENGTH, WIDTH, AND HEIGHT

3.3 Packed Canister Size and Dimensions

3.3.1 Table 1: Volume, Absorbent Quantity and Bulk Density

TEST NO.	CANISTER NO.	VOLUME (LITERS)	WT. GRAN. (GRAMS)	BARALYME (POUNDS)	BULK DENSITY (GM. G.B./100CM^3)
1	A1	2.805	2930	6.46	104.4
2	A1	2.805	2950	6.51	105.2
3	A1	2.805	3010	6.64	107.3
5	B1	1.960	1955	4.31	99.7
6	B1	1.960	2030	4.47	103.6
7	C1	2.117	2140	4.75	101.1
8	C1	2.117	2170	4.78	102.5
9	E1	2.264	2590	5.71	114.4
11	E3	2.470	2590	5.71	104.9
12	E3	2.470	2660	5.86	107.8
13	E4	1.740	2020	4.45	116.1
14	E4	1.740	1940	4.27	111.5
15	E4	1.740	2020	4.45	116.1
19	E5	1.829	1971	4.34	107.8
20	E5	1.829	2002	4.41	109.4

3.3.2 Table 2: Dimensional Data (see Figure 2A - 2B)

CANISTER NO.	HEIGHT H.(CM)	BASE A.(CM)	BASE A^1.(CM)	SIDE B.(CM)	VOLUME (LITERS) INLET	EXHAUST
A1	36.8	16.6	13.9	5.0	0.640	0.635
B1	28.5	14.5	13.0	5.0	0.340	0.325
C1	23.5	18.5	17.5	5.0	0.505	0.500
E1-E2	18.0	17.8	16.1	6.6	0.500	0.490
E4	13.7	17.7	16.0	7.5	0.400	0.400
E5	12.0	20.2	18.3	8.0	0.300	0.300

CANISTER NO.	AREA HB.(CM^2)	PERIMETER 2H + 2B.(CM)	EQUIVALENT DIAMETER(CM)	EQ. MEAN LENGTH (CM)	EQ. L/D RATIO
A1	184.0	83.6	8.80	15.25	1.73
B1	142.5	67.0	8.50	13.75	1.62
C1	117.5	57.0	8.24	18.00	2.18
E1-E3	118.8	49.2	9.66	16.95	1.76
E4	102.8	42.4	9.88	16.85	1.70
E5	96.0	40.0	9.60	19.21	2.00

(NOTE: Definitions and computations of equivalent diameter and "equivalent mean length": para. 4.6.1)

3.4 Table 3: Ventilation and CO_2 Loading

TEST NO.	CANISTER NO.	MINUTE VOLUME (LPM, STPD)	PEAK FLOW (LPM, STPD)	CO_2 OUTPUT (LPM, STPD)	TOTAL CO_2 THRU CANISTER (L, STPD)
1	A1	26.10	81.95	1.174	247
2	A1	25.60	80.38	1.152	219
3	A1	25.90	81.33	1.166	187
5	B1	26.40	82.90	1.188	27
6	B1	26.10	81.95	1.174	72
7	C1	26.10	81.95	1.174	118
8	C1	26.60	83.52	1.197	90
9	E1	26.05	81.80	1.172	125
11	E3	25.60	80.38	1.152	126
12	E3	26.00	81.64	1.170	184
13	E4	27.38	85.97	1.232	65
14	E4	26.05	81.80	1.172	19
15	E4	26.29	82.55	1.183	24
19	E5	27.12	85.16	1.220	119
20	E5	26.49	83.18	1.192	145

3.5 Table 4: Duration and Efficiency

TEST NO.	CANISTER NO.	TIME (MINUTES) TO TRACE CO_2	0.25% CO_2	0.50% CO_2	MINUTES PER 100GM.	LITERS CO_2 ABSORBED PER 100GM.	TOTAL
1	A1	32	164	210	7.2	7.9	232
2	A1	60	140	190	6.4	7.2	209
3	A1	15	90	160	5.3	5.8	165
5	B1	5	12	23	1.2	1.4	27
6	B1	7	23	61	3.0	3.4	69
7	C1	12	76	104	4.8	5.4	116
8	C1	4	58	75	3.5	4.0	87
9	E1	1	67	107	4.2	5.0	119
11	E3	8	35	109	4.2	4.5	117
12	E3	0	98	157	5.9	6.3	167
13	E4	0	20	53	2.7	3.1	63
14	E4	0	7	16	0.8	0.9	17
15	E4	0	5	20	1.0	1.1	22
19	E5	15	35	97	4.9	5.9	116
20	E5	7	80	122	6.1	7.0	141

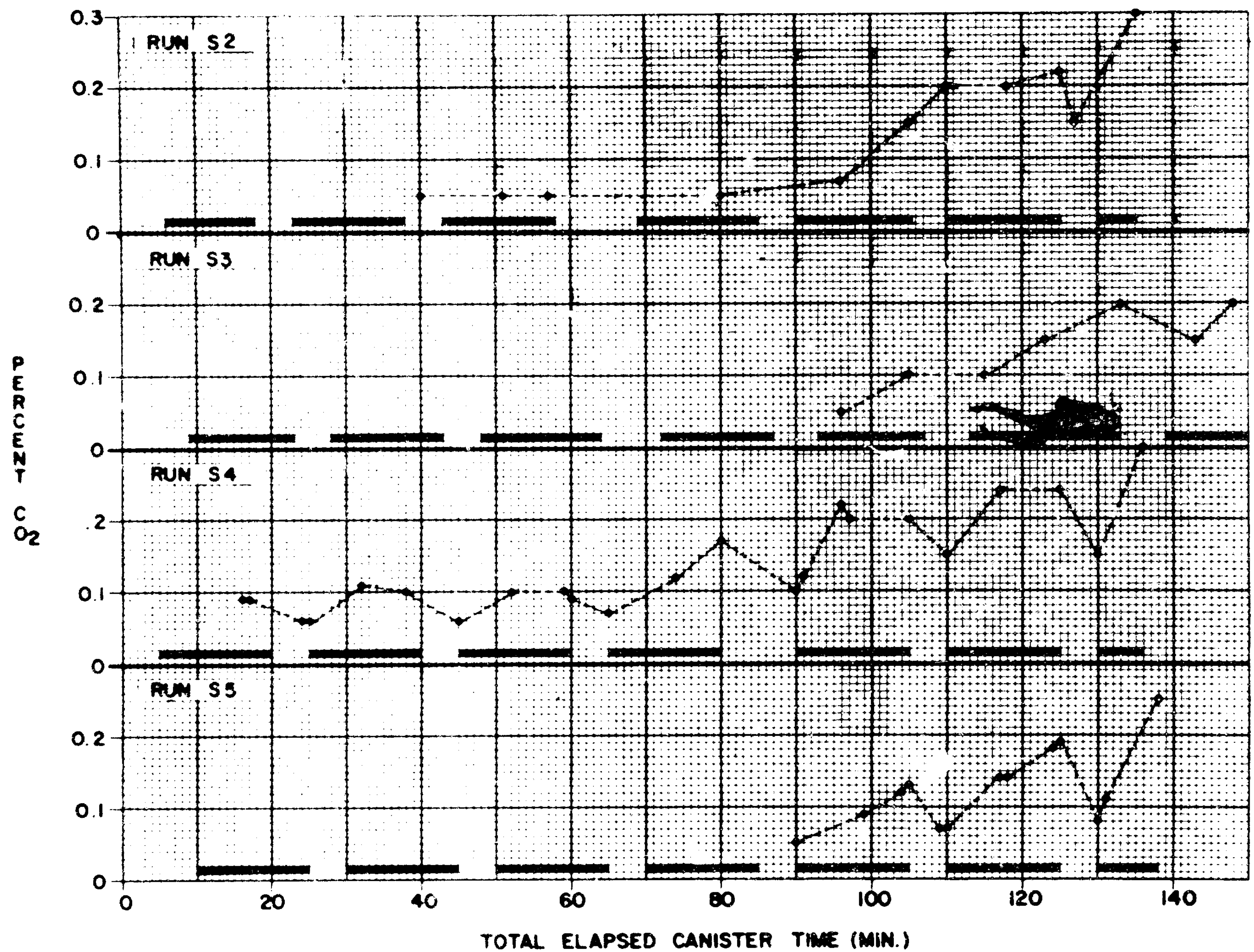
3.6 Table 5: Flow and Resistance to Flow

TEST NO.	CANISTER NO.	ΔP ($CM\ H_2O$) AT PEAK FLOW INITIAL	AT F_{CO_2}=0.25%	RESISTANCE ($CM\ H_2O$/L/SEC) AT PEAK FLOW (AT F_{CO_2}=0.25%)
1	A1	1.7	3.0	2.2
2	A1	2.0	2.4	1.7
3	A1	2.0	2.2	1.6
5	B1	2.0	2.2	1.6
6	B1	2.4	2.8	2.0
7	C1	1.6	2.0	1.5
8	C1	3.3	4.1	2.9
9	E1	2.2	2.7	1.9
11	E3	3.0	3.3	2.5
12	E3	2.7	3.0	2.2
13	E4	3.8	4.1	2.2
14	E4	3.3	3.5	2.6
15	E4	3.5	3.5	2.5
19	E5	2.8	3.0	2.1
20	E5	2.7	3.5	2.5

3.7 Table 6: Miscellaneous Parameters

TEST NO.	CANISTER NO.	TEMPERATURE (°C) AMBIENT	INPUT GAS	THEORETICAL CO_2 CAPACITY (L, STPD)	REYNOLDS NO. (AIR, 20°C, 1ATM, ABS)
1	A1	25.6	29.4	712	431
2	A1	23.0	27.4	717	423
3	A1	22.8	27.6	731	428
5	B1	18.5	24.2	475	544
6	B1	20.0	24.5	493	537
7	C1	26.6	30.0	520	632
8	C1	23.0	27.1	527	644
9	E1	26.2	29.7	629	732
11	E3	24.0	28.0	629	719
12	E3	24.0	30.0	646	730
13	E4	22.1	27.2	491	909
14	E4	22.0	26.0	471	865
15	E4	22.0	27.1	491	872
19	E5	25.0	29.4	479	936
20	E5	26.5	29.4	486	961

FIGURE 3. UNDERWATER, CLOSED-CIRCUIT SCUBA RIG SWIMS WITH PROTOTYPE FLATCANS C1 & E3; CANISTER DURATION (SWIM & REST PERIODS) FROM TIME ZERO UNTIL INHALED CO_2 FRACTION = 0.25%



3.8 Table 7: Underwater Swimming Test Results

TEST NO.	CANISTER NO.	TIME(MINUTES) TO ANALYSIS OF TRACE CO_2	0.1% CO_2	0.2% CO_2	0.25% CO_2	WT. GRANULAR BARALYME (LB.)
S1	A1	10	45	-	100	6.7
S2	C1	41	98	110	134	4.5
S3	C1	96	105	133	154	4.4
S4	E3	16	32	95	136	6.1
S5	E3	90	104	136	138	6.0
S6	B1	51	59	*	*	4.6
S7	E5	10	35	95	96	4.2
S8	E5	25	67	*	*	5.0

(NOTE: Run No. S6 terminated due to flooding of rig at + 68 minutes; final CO_2 analysis was 0.06%; run No. S8 terminated after 90 minutes due to gas supply exhaustion; final CO_2 analysis was 0.15%

3.9 Table 9: Recompression Chamber Test Results

3.9.1 Subjective Runs with Air

	SURFACE	33 FEET	66 FEET	99 FEET
C: Tidal Volume(L,STPD)	2.18	1.99	1.66	1.84
H:	2.50	1.77	1.75	1.83
I:	2.44	1.78	1.85	1.97
C: Peak Flow(L/SEC,STPD)	0.90	0.72	0.77	0.75
H:	0.85	0.61	0.65	0.68
I:	0.87	0.61	0.66	0.64
C: ΔP at Peak Flow(CM H_2O)	0.41	0.76	0.94	1.09
H:	1.52	1.02	1.66	1.73
I:	1.31	1.81	2.10	2.89

(NOTE: "C" = Flatcanister No. C; "H" and "I"=cylindrical canisters having same Baralyme capacity as FLATCAN C (reference 4)).

3.9.2 Mechanical Respirator Runs (air)

CANISTER NO.	SURFACE	ΔP(CM H_2O) FOR AIR, AT PEAK FLOW 33 FEET	66 FEET	99 FEET	198 FEET	330 FEET
FLATCAN A	1.0	1.5	2.1	2.5	4.5	6.5
FLATCAN C	1.4	1.9	2.7	3.8		
FLATCAN E4	1.2	1.9	2.1	2.2		
CYLINDIRCAL H	3.1	4.8	6.0	8.0		
CYLINDRICAL I	4.2	6.8	10.1	13.6		
USN STD. O_2	3.8	5.6	7.3	9.0		
USN MARK VI	5.2	7.6	10.6	13.1	19.6	

(NOTE: Tidal volumes 2.38 - 2.50 liters, STPD)

3.10 Table 9: Statistical Parameters

CANISTER SERIES	NO. OF RUNS	MEAN AND STANDARD ERROR OF THE MEAN MIN. TO 0.5% CO_2	CM H_2O/L/SEC, AT PEAK FLOW	REYNOLDS NUMBER
A	3	186.7 ± 14.5	1.83 ± 0.18	427.3 ± 2.0
B	2	42.0 ± 13.4	1.80 ± 0.20	540.8 ± 2.4
C	2	90.0 ± 14.5	2.40 ± 0.70	638.2 ± 4.5
E1-E3	3	124.0 ± 16.3	2.30 ± 0.10	727.0 ± 3.2
E4	3	26.0 ± 8.9	2.30 ± 0.12	882.0 ± 11.2
E5	2	109.5 ± 12.5	2.30 ± 0.20	948.9 ± 12.4

MEAN REYNOLDS NUMBER (N=15), FLATCANS: 690.98
MEAN REYNOLDS NUMBER (N=16), CYLINDRICAL CANISTERS: 1173.68
DIFFERENCE BETWEEN MEANS, AS MEASURED BY A FISHER t TEST, IS SIGNIFICANT AT THE 0.01 LEVEL OF CONFIDENCE

4. DISCUSSION

4.1 Introduction. The discussion sequence, within following paragraphs, opens with descriptive summary information concerning FLATCAN architecture and geometry. Numerical data comparisons of flow and resistance observations are then considered with reference to cylindrical canisters as the (only) standards for comparison, not as standards of an ultimate optimum in functional excellence. A review of diver and apparatus breathing resistance factors in SCUBA systems, and resume of the structural basis of FLATCAN flow properties together provide the fundamental portions of the section.

4.2 Descriptive Summary of FLATCAN Geometry

4.2.1 Description. The basic FLATCAN is comprised of first and second perforate wall portions for confining the absorbent chemical, with the wall portions inclined with respect to one another and bounded by gas inlet and gas exhaust chambers to provide a configuration which may be characterized (two-dimensional aspect) as a truncated isosceles trapezoid. With the perforate walls forming sides thereof, imperforate rectangular walls forming the top and the base, and the imperforate trapezoidal walls forming front and rear it is (three-dimensional aspect) a frustum of a rectangular pyramid. With inlet and exhaust conduits included, the overall package presents as a rectangle, exteriorly.

4.2.2 Canister Cover Assembly. As indicated by figures 2A and 2B, the disposition of the packed granular absorbent is such that it projects somewhat above the actual screen-to-screen transverse gasflow zone. The tension bar component of the cover assembly serves to maintain the granular mass rigidly in place, and is therefore, functionally analagous to the spring-loaded end-plate screens of cylindrical canisters. It is believed that opportunities for gas-stream channeling, with consequent canister failure, can be minimized by this mechanism because the cover assembly exerts tension which is uniformly transmitted to the "granular reserve", tending to force it downward.

Migration of these granules would compensate for voids appearing adjacent to the bulkheading subsequent to, e.g., insufficient packing, settling of granules, or shifting caused by vibrations and postural changes. It is recognized, however, that the desirable canister-cover tension might be difficult to establish and that proper locknut positioning is overly critical in terms of an evolution which demands practical utility. Several alternative cover and lid assemblies have been tested, and it is concluded that a number of satisfactory types can be designed. Absorbent-filled cartridge inserts, prepacked and disposable, may be logistically as well as operationally of great value with this canister. This concept will be evaluated.

4.2.3 The Acronym. Origination of the words FLATCAN and FLATCANISTER (patent pending) is from the following morphological-functional descriptive phrase: flat, low-resistance, carbon-dioxide absorption trapezoidal canister.

4.3 Comparisons of Flatcanisters and Cylindrical Canisters

4.3.1 Gasflow Data Analysis Requirements. Complexities are not unexpected in comparative studies of hydraulic phenomena of distinct flow conduit systems. The spectrum of parameters which may require attention can be simplified, however, by organization into at least three categories.

(a) Geometric parameters: e.g., the finite boundaries of the conduits, tubing, pipes, hoses, etc.;

(b) Kinematic parameters: with respect to flow conditions at specified structural sites; this includes velocity and time factors;

(c) Force parameters: the influences acting upon flowing gases, including gravity, inertia, surface tension, viscosity and compressibility;

4.3.2 Reynolds Number. It has been established that the behavioral phenomena of fluids flowing within conduits depend upon whether the flow is laminar, i.e., in lamina or layers parallel to the tube walls, or turbulent. Differing velocities characterize the conceptual "layer" of flowing fluid. Reynolds discovered that the nature of fluid flow is primarily a function of the conduit inside diameter, the average velocity, and the fluid density and viscosity. These parameters can be combined, with consistent units, to produce the dimensionless constant, Reynolds number, which expresses the ratio of inertial forces to viscosity forces within a defined hydraulic system. When it is less than 1,000, gas flow is presumed to be laminar. Turbulent flow occurs in association with Reynolds numbers which exceed 1,500 - 2,000.

4.3.3 (a) REYNOLDS NUMBER = (VELOCITY)(REFERENCE LENGTH)(DENSITY)/VISCOSITY
(b) VELOCITY = VOLUME FLOW/CROSS-SECTIONAL AREA
(c) REFERENCE LENGTH = DIAMETER (CIRCULAR CROSS-SECTION)
(d) REFERENCE LENGTH = EQUIVALENT DIAMETER (RECTANGULAR CROSS-SECTION)
(e) EQUIVALENT DIAMETER = (AREA/PERIMETER)(4)

4.3.4 <u>Specimen Calculation</u>

(a) For air, one atm. abs pressure, 20°C, density = 0.0012047 GM/CM^3; absolute viscosity = 0.0001813 POISE (GM/CM·SEC);

(b) From data of run number 1, Flatcanister A1, velocity = 7.42 CM/SEC; equivalent diameter = 8.8 CM;

(c) REYNOLDS NUMBER = (7.42)(8.8)(0.0012047)/0.0001813 = 431

4.3.5 <u>Airflow and Resistance to Flow: Data Comparisons</u>. Mean data for cylindrical canisters originates with those observations already reported (4) for sixteen breathing machine experiments.

TABLE 10

OBSERVATION, OR COMPUTED INDEX	CYLINDRICAL CANISTERS (N=16)	FLATCANISTERS (N=15)	MEAN DIFFERENCE
Reynolds number	1173.7	691.0	482.7 (P=0.01)
initial ΔP(CM H_2O)	5.88	2.60	3.28
ΔP, F_{CO_2} = 0.25%	7.10	3.02	4.08
ΔP, F_{CO_2} = 0.50%	7.64	3.20	4.44
CM H_2O/L/SEC at peak flow, F_{CO_2} = 0.50%	5.21	2.15	3.06

4.3.6 <u>CO_2 Elimination: Mean Data Comparisons</u>. Table 11 (following) indicates that Flatcanisters are less efficient than comparable-capacity cylindrical canisters in removing carbon dioxide from the "exhaled" gas in the standarized breathing machine-type test. The minimal-capacity category may, however, prove to be an exception in this respect. These observations have not proven to be a source of concern because operational canisters should routinely be constructed to have reserve capacity, and because the Flatcanister size-dimension-duration relationships have been deduced. Canister E5, for example, represents a deliberate effort to obtain 80-100 minutes duration to the endpoint. Moreover, there seems to be but little doubt that retention of endogenous carbon dioxide by a working diver, at depth, is potentially more hazardous than is the inhalation of a gas mixture containing less than one-half of one percent (by volume, referenced at the surface) carbon dioxide.

TABLE 11

CANISTER TYPE	NUMBER	CO_2 CAPACITY (LITERS)	LITERS CO_2 ABSORBED/100GM BARALYME	DURATION TO 0.5% CO_2 (MIN)
Cylindrical	16(all)	687	6.4	18[illegible]
Flatcanisters	15(all)	566	4.6	100
Flatcanisters	12(functional)	527	5.3	118
Cylindrical	3	715	8.3	219
Flatcanisters	3	721	7.0	187
Cylindrical	2	637	7.7	179
Flatcanisters	3	637	5.3	124
Cylindrical	3	447	5.3	79
Flatcanisters	4	483	6.4	100

4.4 Breathing Resistance External to the Diver's Airway

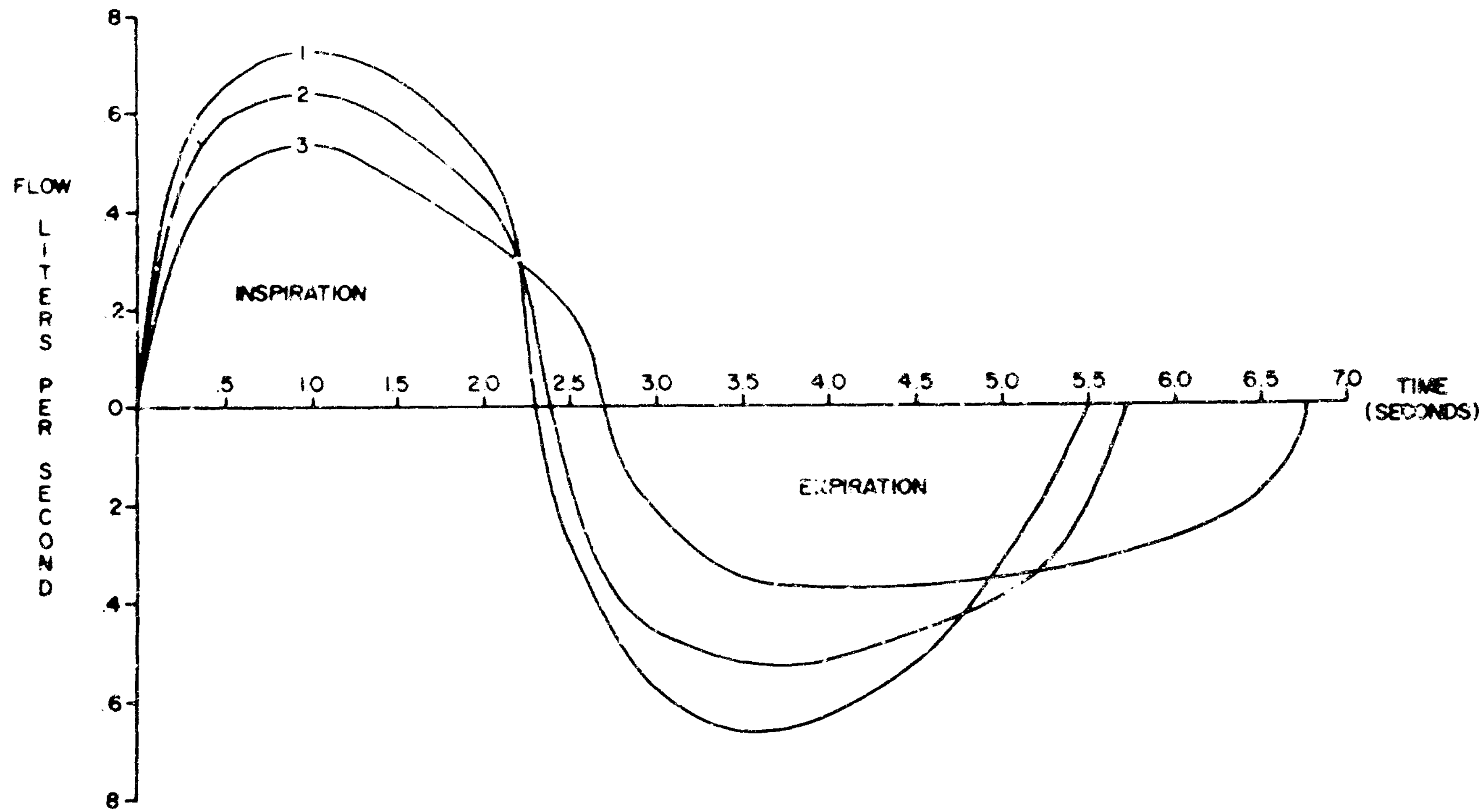
4.4.1 Definitions. Breathing apparatus serves no rational function apart from the user who is co-equally an intrinsic division of this man-machine system. If resistance consists of opposition to motion, then breathing resistance refers to impedance of respiratory airflow and, consequently, has units of FORCE/FLOW, e.g., CM H_2O/LITER/SECOND. Airflow resistance evaluations require the simultaneous determination of system flowrate and pressure differential. The following statement, although oversimplified and not all-inclusive, facilitates sharp focusing upon the basis of the resistance concept: The cause of the resistance properties of essentially rigid-wall apparatus components is the forces of friction, the mechanism of action consisting of the transformation of kinetic energy of gas molecules to heat energy, which is subsequently lost or dissipated.

4.4.2 Resistance Effects Upon Respiratory Patterns. Increasing external apparatus resistance loads usually alter ventilatory mechanics, alveolar ventilation, blood acid-base homeostasis and cardiac output in predictable directions, and variable magnitudes:

(a) Increased time of each phase
(b) Decreased maximal flowrate
(c) Decreased time to attain maximal flow
(d) Decreased mean flowrate
(e) Increased peak pressure of each phase
(f) Flattening of the expiratory waveform
(g) Increased expiratory reserve volume
(h) Decreased pulmonary ventilation
(i) Decreased alveolar ventilation
(j) Increased alveolar P_{CO_2}
(k) Decreased alveolar P_{CO_2}
(l) Increased cardiac minute olume in inspiration
(m) Decreased cardiac minute volume in expiration

4.4.3 Resistance and Respiration: Summary. (1)(11)(13)(16). Normal respiration is altered by frictional resistance associated with dense-gas motion within the anatomical airways as well as within the tubes, hoses and conduits of the external apparatus airway. Increased breathing pressures are then required for adequate flow to be attained and sustained, thereby requiring that muscular efforts of breathing be augmented. Because the time span of a phase of respiration lengthens as resistance mounts, the respiratory rate per minute must diminish. The expiratory phase, particularly, is susceptible to such prolongation and this may, in turn, be linked into further steps of a cycle: should the stimulus to inhale appear prior to full exhalation of sufficient gas volume, a state of relative hyperinflation of the lungs can be induced. Alveolar ventilation, therefore, is progressively more compromised, and results in the shift to a less physiologically favorable equilibrium of alveolar ventilation and alveolar carbon dioxide tension. Assuming that carbon dioxide production has been increased from representative resting amounts to magnitudes associated with underwater working experiences, and that chest muscle and diaphragm muscle metabolic demands have escalated, it follows that the organism cannot continue to eliminate sufficient carbon dioxide, in unit time, to compensate both for compromised ventilation and several components of accelerated production.

FIGURE 4. EFFECTS OF EXTERNAL, ADDED RESISTANCE ON THE RESPIRATORY CYCLE OF RESTING SUBJECTS (1) CONTROL, (2) ADDED RESISTANCE = 6.7 CM H_2O/L/SEC; (3) ADDED RESISTANCE = 30.8 CM H_2O/L/SEC



Molecular carbon dioxide retention with resulting acute respiratory acidosis may occur. Breathing mixtures with increased oxygen tensions, in particular those with PO_2 greater than one atmosphere absolute, introduce another element into the cycle. It has been clearly demonstrated that oxygen acts to diminish the sensitivity of the central respiratory center to carbon dioxide, thereby impairing the capability of the ventilatory route for eliminating CO_2 (7)(9). The significance of this mechanism in working, high-oxygen, underwater circumstances cannot be dismissed. The cycle of interacting causes, influences, and effects, then includes:

(a) increasing susceptibility to both subtle and obvious oxygen effects, such as,
(b) loss of consciousness during high-level exercise swimming with 100% O_2 or dense N_2-O_2 mixtures;
(c) interaction of CO_2 and inert gases in the mechanisms culminating in depth narcosis and performance impairment;
(d) specific undesirable actions of CO_2 and metabolities upon acid-base balance, etc., and probable role of CO_2 in bubble formation and/or bubble growth.

4.4.4 Quantitative Examples of Resistance Effects

(a) Consequences of added external resistance, (6.4 CM H_2O, inspiration; 4.1 CM H_2O, expiration) during resting intervals and at two levels of working exertions, selected from the data of Silverman, et.al. (14)(15):

TABLE 12

OBSERVATION	CONTROL DATA	ADDED RESISTANCE DATA
breaths/minute, rest	14.6	14.8
heavy work	30.4	27.4
maximal work	47.6	42.0
resp min volume, rest	10.3 LPM	9.1 LPM
heavy work	54.7	48.9
maximal work	113.8	90.3
peak insp flow, rest	40.0 LPM	31.0 LPM
heavy work	149	128
maximal work	286	240
peak exp flow, rest	32 LPM	29 LPM
heavy work	154	144
maximal work	322	274

(b) The following data, for resting subjects, was reported by Cain and Otis(1). Figure 4, which compares the effects of resistance upon respiratory waveforms, has been prepared to illustrate this information from their paper.

TABLE 13

OBSERVATION	RESISTANCE in CM H_2O/LITER FLOW/SECOND 7.70	14.40	38.50
breaths/minute	12.0	10.1	7.4
resp min volume	10.15 LPM	9.37 LPM	8.98 LPM
peak insp flow	42.6 LPM	39.2 LPM	31.6 LPM
peak exp flow	39.1 LPM	30.8 LPM	43.0 LPM
alveolar oxygen tension	99.2 mm Hg	-	96.1 mm Hg
alveolar carbon dioxide tension	40.6 mm Hg	-	42.4 mm Hg

(c) Zechman, Hall and Hull (16) have demonstrated the following effects of graded resistance to airflow in eleven subjects. Dramatic changes occured with moderate exercise.

TABLE 14

RESISTANCE	LITERS/MINUTE (BTPS) REST	EXERCISE	ALVEOLAR P_{CO_2} (mm Hg) REST	EXERCISE
(1. Both inspiration and expiration)				
Control	7.90	22.6	36.6	41.7
10CM H_2O/L/SEC	7.08	20.2	37.3	44.1
22	6.59	18.4	37.6	46.3
32	6.50	17.2	38.4	51.2
43	6.26		38.8	
(2. Expiration only impeded)				
Control	7.70	23.5	36.0	40.3
10CM H_2O/L/SEC	7.50	21.2	36.0	41.9
22	7.00	20.1	36.2	43.4
32	6.96	19.7	36.7	43.5
43	6.54		36.9	
(3. Inspiration only impeded)				
Control	7.76	23.5	36.7	41.8
10CM H_2O/L/SEC	7.39	21.7	36.9	42.5
22	7.32	21.6	37.2	42.7
32	7.15	20.8	37.2	43.0
43	6.78		38.0	

4.4.5 Biomedical Engineering of Divers' Breathing Mixtures and Apparatus. Characteristic of man is his inborn unsuitability for the stresses of subaquatic exposures. Neither the curious practices and techniques of many divers, some of whom are still living, nor the undoubtedly unphysiological characteristics of certain breathing devices have significantly altered the surface-dwellers respiratory anatomy and function. Providing divers with breathing apparatus which significantly increases the work of breathing is the same as ordering the preferential selection of asthmatics for diving duty. Recent studies by the Experimental Diving Unit(5) have explored the effects of apparatus airway properties and breathing mixture composition and density upon respiration and ability to perform useful work at depth. The primary object was the definition of deep-diving gas-mixture requirements, with the basic experimental hypothesis being the assumption that optimal conditions could be considered with reference to the diver and the immutability of his physiological needs. Apparatus characteristics were expressed in a similiar hypothesis. The FLATCAN represents a developmental product of this experimental design approach, in which emphasis rests with the diver as the only unalterable portion of the system.

4.5 Swim and Chamber Run Data

4.5.1 Subjects, Methods, Diver Acceptance.

(a) Swimming run subjects were, when feasible, preferentially selected according to the accumulated data which described their ventilation and CO_2 production responses to the 0.8 knot trapeze ergometer load or the 1.5 liter per minute oxygen consumption pump ergometer load(5). The duration data (Table 7) was also influenced by at least one other procedural bias: withdrawal of gas to the sampling and analysis tubing and apparatus is analagous to converting from a closed to a semi-closed circuit system. Figure 3 relates total use time and swim-rest patterns of four runs.

(b) The initial, understandably skeptical attitudes which were encountered were intense but brief. Requirements for thermal insulation of the lucite prototype canisters were vociferously noted.

4.5.2 Chamber Runs. Agreement between the reported results (pressure drop) and predictive extrapolations derived by the Graham Law relationship were consistent and close. While exhaling through the smaller cylindrical canister systems there was an unexpectedly prominent subjective awareness of the flow impedance. The requirement for obtaining suitable high-pressure environment flow sensor and data display instrumentation, compatible with the restrictions of decompression, and procedural limits which effect working time at depth, was clearly apparent. Flatcanister A1 was run at 330 feet with the breathing machine. ΔP at peak flow, 6.5 CM H_2O, has been exceeded at one atmosphere absolute by several of the cylindrical canisters.

4.6 Structure-Function Aspects of the FLATCAN.

4.6.1 "Equivalent" Length-Diameter Ratios.

(a) The ratio of flowpath length to cross-sectional diameter seems to provide a convenient and valid index for relating flow resistance and static pressure drop to length(direct relationship) and circular cross-sectional area(inverse relationship). The cylindrical canisters with highly efficient absorption functioning are, in general, those which present higher-range flow impedance. Small, low-resistance canisters have consistently proved to be non-functional with reference to current concepts of safe diving standards. Dual properties of low flow resistance and high absorptive efficiency characterize the largest cylindrical canisters. Current operational USN rig canisters can be placed within a category between these extremes. Briefly summarized, these structure-performance correlations are as follows:

CANISTER SIZE	LENGTH/DIAMETER RATIO	RESISTANCE CHARACTERISTIC	CO_2 ABSORPTION
small	low	optimal	poor
small	high	excessive	poor to fair
medium	medium	high	fair to good
medium	high	excessive	fair to good
large	low	optimal	good
large	medium	medium	good

(b) Hydraulic radius and equivalent diameter were computed in compliance with gas flow system study practices and were used to estimate the flow effects of square and rectangular cross sectional faces and radius of curvature ratios of conduit bends. The following tabulations show the procedure and the computation sequence used to derive the "mean equivalent" length-diameter ratios for flatcanister developments:

TABLE 15

A. PROCEDURE

(1) PERPENDICULAR HEIGHT x BASE (HB) = CROSS-SECTIONAL AREA
(2) PERPENDICULAR HEIGHT x 2 plus BASE x 2 = WETTED PERIMETER
(3) AREA divided by PERIMETER = MEAN HYDRAULIC RADIUS OF THE RECTANGLE
(4) MEAN HYDRAULIC RADIUS x 4 = EQUIVALENT DIAMETER

(NOTE: Derivation by assuming the analogy to the case of the circular cross-section, in which AREA = πr^2; PERIMETER = $2\pi r$; $\pi r^2/2\pi r$ = MEAN RADIUS; $2r$ = DIAMETER; $r = D/2$; $r/2 = D/4$; MEAN HYDRAULIC RADIUS x 4 = DIAMETER)

B. EQUIVALENT DIAMETERS OF RECTANGULAR CROSS-SECTIONS

CANISTER NO.	HEIGHT	X	BASE	divided by	PERIMETER	= MHR	X 4 = EQ. DIA
A	36.8	X	5.0 =	184.0 ÷	83.6	= 2.20	8.80
B	28.5		5.0	142.5	67.0	2.13	8.52
C	23.5		5.0	117.5	57.0	2.06	8.24
E1-E3	18.0		6.6	118.5	49.2	2.41	9.64
E4	13.7		7.5	102.5	42.4	2.47	9.88

C. EQUIVALENT LENGTH-DIAMETER RATIOS

CANISTER NO.	BASE(A)	+ BASE(A¹)	divided by 2 = MEAN LENGTH"	divided by EQ.DIA = L/D RATIO	A / EQ.DIA	A¹ / EQ.DIA
A	16.6	13.9	15.25	1.73	1.58	1.88
B	11.5	13.0	13.75	1.62	1.53	1.71
C	18.5	17.5	18.00	2.18	2.12	2.24
E1-E3	17.8	16.1	16.95	1.76	1.67	1.84
E4	17.7	16.0	16.85	1.70	1.62	1.79

(NOTE: The mean length, A + A¹/2, divided by equivalent diameter = mean equivalent length-diameter ratio; A/EQ. DIA. and A¹/EQ. DIA. represent the presumed boundary extremes of this ratio)

(c) Suitable emphasis is, perhaps, facilitated with reference to specific examples of the relationships, introduced above, of dimensions, size and function. The presentation of mean data for a spectrum of graded cylindrical canisters (paragraphs 4.3.4 - 4.3.5) necessarily obscures this perspective. This data, extracted from EDU Research report 3-64, is arranged in the same manner as the listing of hypothetical correlations, with which this paragraph (4.6.1(a)) began. Note that the efficient, low resistance canisters are the largest ones of the series.

TABLE 16

CYLINDRICAL CANISTER SIZE	LENGTH/DIAMETER RATIO	MINUTES TO 0.5% CO_2/100GM	RESISTANCE (CM H_2O/L/SEC) AT PEAK FLOW
small, wide	1.97	1.6	2.8
small, medium	2.68	4.4	5.0
small, narrow	2.76	2.1	14.0
medium, medium	3.80	7.0	7.3
medium, narrow	4.67	7.7	7.6
large, wide	2.72	6.9	3.4
very large, wide	3.27	9.1	5.0

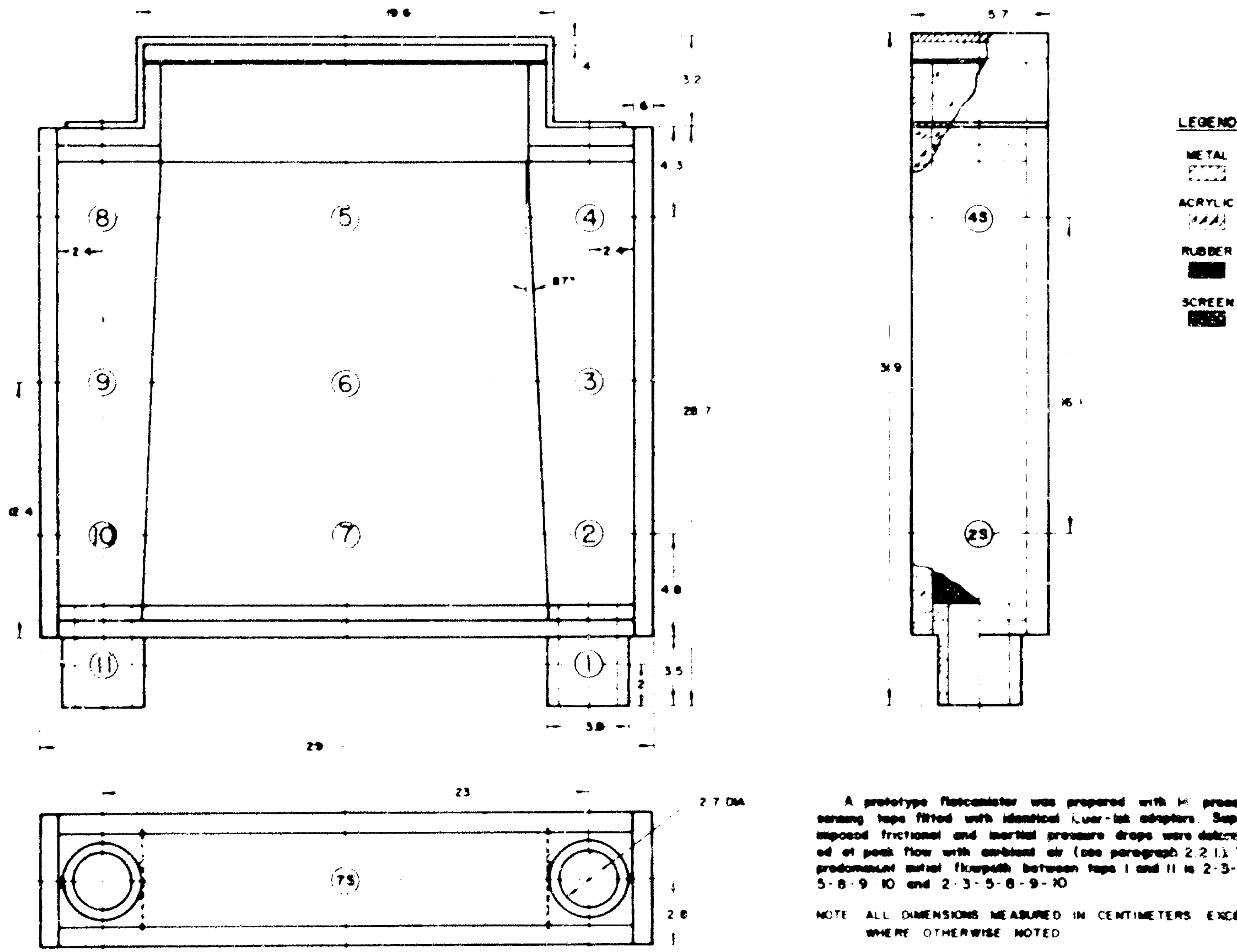
4.6.2 Absorbent Chamber Volume. Size-duration data correlations indicate that an effectively non-functional minimal capacity exists for the FLATCAN, and that it is reached at 1.8 liters, the chamber volume magnitude described for the "theoretical minimal cylindrical canister"(4). Additional observations with small FLATCANS, data not reported, reinforce this provisional estimate.

4.6.3 Conduit Cross-Sections. Cylindrical canisters derive form resistance related to each abrupt change in cross-sectional size. Expansions and contractions are inherent, for example, at each hose-fitting-plenum chamber boundary. In contradistinction, the FLATCAN has been assembled without abrupt cross-sectional changes of comparable orders of magnitude. The design incorporates transitions: sections of conduit which interconnect adjacent prismatic portions, one to another, with gradual change in cross-sectional geometry (12). The pressure-drop concomitants of these contrasting conduit designs are more-or-less analagous to those of a flat-plate orifice-venturi throat comparison. Flat-plate orifices usually entail rather large pressure losses. The venturi section, with its transition, usually has the smallest pressure loss of any "engineered obstruction".

4.6.4 Preferential Flowpath Principle. The most obvious predetermined flow characteristic of the cylinder is that all exhaled breaths must traverse the same three-dimensional channel. With the progress of canister-use time, accumulating water of reaction and condensate, together with clotted or slurried, non-functional granules provides the basis for the steadily mounting flow impedance. The gradually-elongating granular flowpath of the flatcanister is the primary structural property acting to minimize resistance, because it exploits the "path-of-least-resistance" phenomenon. With the fresh-charged canister, the shortest inlet-to-exhaust path becomes the site for preferential flow and, therefore, flow obstruction by moisture and slurry initially appears there. Gradually, as canister use time mounts, the preferential flowpath shifts obliquely away from base A1 (figures 2A - 2B) and toward base A. Flow resistance increase as a function of elapsed use time is shown in the following examples (Cylindrical canister data, reference 4):

TABLE 17

FLATCANISTER NO.	CM H_2O ΔP AT PEAK FLOW INITIAL	AT F_{CO_2} = 0.25%	0.50%
A1	1.9	2.5	2.6
B1	2.2	2.5	2.7
C1	2.4	3.0	3.3
E1-E3	2.6	3.0	3.3
E4	3.5	3.7	3.7
E5	2.8	3.3	3.6
CYLINDRICAL CANISTER NO.			
A	4.6	6.7	6.7
B	6.9	9.4	12.0
C	4.1	5.2	5.9
D	3.5	4.3	4.4
E1	7.6	8.2	8.2
I	17.7	19.0	20.4



A prototype flatcanister was prepared with [illegible] pressure sensing taps fitted with identical Luer-lok adapters. Superimposed frictional and inertial pressure drops were determined at peak flow with ambient air (see paragraph 2.2.1.). The predominant initial flowpath between taps 1 and 11 is 2-3-4-5-8-9-10 and 2-3-5-6-9-10

NOTE ALL DIMENSIONS MEASURED IN CENTIMETERS EXCEPT WHERE OTHERWISE NOTED

FIGURE 5. PREFERENTIAL FLOWPATH DETERMINATIONS

4.6.5 Pressure Drop Pattern Determinations. Within limitations set by pressure transducer-amplifier-recorder channel availability, the hypothesis of a gradually-shifting flowpath was tested. Figure 5 illustrates the number and distribution of the pressure sensing taps, and the accompanying legend summarizes certain details of canister preparation, testing and results. These observations verify the preferential flowpath geographical predictions.

4.7 Final Notes

4.7.1 No concrete, tangible proof can be cited in support of suggestions that apparatus flow resistance is intimately linked within a cycle of pre-accident events, even though the experimental and operational evidence does support this concept. This accumulated information, largely unpublished, has been obtained by both mechanical and subjective experimental methods, with canisters alone, with assembled operational rigs, and with a special minimal-resistance device, at ambient pressures between one and eleven atmospheres absolute, during working as well as resting exposures with respired gas mixtures selected by experimental control of individual variables, e.g., mixture density (0.3772 to 9.061 grams per liter), inspired oxygen partial pressure (0.18 to 3.17 atmospheres absolute) and mixture composition (air, 100% oxygen, seven helium-oxygen mixtures, argon-oxygen and neon-oxygen).

4.7.2 The resistance characteristics of most current apparatus are satisfactory, with reference to routine operational exposures. However, certain devices are likely to present positive hazards to the diver, according to the severity of circumstances, in particular those in which oxygen depth-time limits have been exceeded. The FLATCAN type will ease unfavorable flow impedances of assembled divers' breathing apparatus.

4.7.3 No indictment of specific apparatus is implicit in the foregoing remarks. An initial assumption of engineering competance has, in fact, been strengthened. A bio-engineering approach to equipment design can be erected on contemporary foundations of engineering empiricism (2)(3)(8).

4.7.4 Estimates of complexity of Flatcanister manufacture and incorporation, with other components, into suitably comfortable, streamlined, effective rigs have been invited from several sources. The consensus is one of uncertainty.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 It is concluded that:

5.1.1 The FLATCAN is an effective canister and that is has highly favorable flow resistance qualities and in this respect it is particularly suitable for use with divers' breathing apparatus.

5.2 It is recommended that:

5.2.1 The Flatcanister configuration be considered for adaptation to closed-circuit oxygen devices because external airway resistance may predispose certain divers to underwater convulsions;

5.2.2 The Flatcanister configuration be employed in apparatus designed for diving to depths in excess of current experimental exposures, assuming that the granular chemical absorption method for carbon dioxide elimination will be used with such apparatus.

6. ACKNOWLEDGEMENTS

For guidance and advice related to engineering mathematics and elementary fluid dynamics, patent laws, and statistical procedures, we are indebted to Mr. J. Stockard, engineer, Code 636, BUSHIPS, LCDR J. Harter, USN Project Officer, Experimental Diving Unit, Mr. H. David, patent attorney, BUSHIPS, and LT R. Doll (MSC) USN, Experimental Psychologist, Experimental Diving Unit. For sincere scepticism, suggestions and support we are grateful to CAPT. R. D. Workman (MC) USN.

7. REFERENCES

1. Cain, C. E. and A. B. Otis. Some physiological effects resulting from added resistance to respiration. J. Aviation Med. 20:149-160, 1949.

2. Duffner, G. J. Canister design criteria of carbon dioxide removal from SCUBA. Experimental Diving Unit Research report 9-57, 1957.

3. Goodman, M. W. A study of carbon dioxide elimination from SCUBA, with standard and modified canisters of the U. S. Navy closed-circuit oxygen rig. Experimental Diving Unit Research report 1-64, 1964.

4. Goodman, M. W. Carbon dioxide absorption systems for SCUBA. 1. Quantitative considerations of design and performance of cylindrical canisters. Experimental Diving Unit Research report 3-64, 1965.

5. Goodman, M. W. and C. W. Duff. Hyperbaric narcosis: Effects of interacting gas mixture metabolic and physical properties and consequences of breathing-system configurations as determinants of performance capability, ventilatory adequacy and acute respiratory syndromes at depth. BUSHIPS Project FO 11 06-01, Task 3361, Test 6. (Project report 1 in preparation).

6. Huseby, H. W. S. and E. J. Michelsen. Carbon dioxide absorbent evaluation and canister design. Experimental Diving Unit Research report 1-60, 1959.

7. Lambertsen, C. J., P. Hall, H. Wollman and M. W. Goodman. Quantitative interactions of increased PO_2 and PCO_2 upon respiration in man. Ann. N.Y. Acad. Sci. 109:731-741, 1963.

8. Leyden, C. J. Breathing resistance in SCUBA components. Experimental Diving Unit Research report 4-57, 1957.

9. Lloyd, B. B., M. G. Jukes and D. J. C. Cunningham. The relation between alveolar oxygen pressure and the respiratory response to carbon dioxide in man. Quart. J. Exp. Physiol. 43:214, 1958.

10. McDowall, D. G. Anesthesia in a pressure chamber. Anesthesia 19:321-336, 1964.

11. Milic-Emili, J. and J. M. Tyler. Relationship between $PACO_2$ and respiratory work during external resistance breathing in man. Ann. N.Y. Acad. Sci. 109:908-914, 1963.

12. O'Rourke, C. E. (editor) General Engineering Handbook. New York: McGraw-Hill Book Company, 1940.

13. Paton, W. D. M. and A. Sand. The optimum intra-pulmonary pressure in underwater respiration. J. Physiol. 106:119-138, 1947.

14. Silverman, L., R. C. Lee, L. Brouha, J. L. Whittenberger, J. F. Stiff, J. E. Byrne, Jr., and D. P. Smith. Fundamental factors in the design of protective respiratory equipment. Endpoint breathing studies. OSRD Report 4229, 1944.

15. Silverman, L., G. Lee, T. Plotkin, L. A. Sawyers and A. R. Yancy. Airflow measurements on human subjects with and without respiratory resistance at several work rates. Arch. Ind. Hyg. 3:461, 1951.

16. Zechman, F., F. G. Hall and W. E. Hull. Effects of graded resistance to tracheal airflow in man. J. Appl. Physiol. 10:356-362, 1957.